# §20. Enhancement of Effective Rate Coefficient in Dense Plasma

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In plasma, dielectronic excited states of ions are produced by dielectronic capture and also by excitation of an already-excited ions. Ions in dielectronic excited states emit satellite lines which are used for determination of the electron temperature of the plasma, a well-known plasma diagnostic measurement. For low density plasma the line intensities can be predicted using the branching ration of dielectronic states while for high-density plasma one must perform collisional-radiative calculations including transition between excited states. We have constructed a collisional-radiative model (CRM) valid for the latter case. For this model we must consider the treatment of dielectronic excited states, which are much more numerous than the singly excited states. We study the effective rate coefficients for excitation, de-excitation and ionization, and recombination through dielectronic states of two-electron ion. Our objective is to establish a way to treat dielectronic excited states.

A CRM on two-electron system including dielectronic excited states was studied by Fujimoto and Kato.1) They study ladder-like excitation-ionization mechanism using CRM of $1s^2$-1snl-1s ionization / recombination series, 1s-2snl-2s and 1s-2pnl-2p excitation / de-excitation series for high density, respectively. We reconstruct a new CRM including singly excited states 1snl and dielectronic excited states 2snl and 2pnl taking into account 2snl-2pnl and 1snl'-2lnl' collsional processes based on Fujimoto and Kato model. Our CRM include excitation / de-excitation, ionization, dielectronic capture, 3-body and radiative recombination by electron impact, radiative transition and autoionization. The rate equations assumed steady-state excluding $1s^2$, 1s, 2s and 2p states, solved for population density N(i) as follow;

$$N_i = r_i^{(0)} n_e N_{1s^2} + r_i^{(1)} n_e N_{1s} + r_i^{(2)} n_e N_{2s} + r_i^{(3)} n_e N_{2p}, \qquad (1)$$

where i is excited state, $r_i$ is population density coefficient, $n_e$ is electron density. The effective rate coefficients using population density coefficients of eq.(1) can be expressed as follow; for example, for 1s-2s excitation / de-excitation,

$$C^{CR}_{2s,1s} = \sum_{i=2}^{\infty} S_{i,1s} n_e r_i^{(2)} + \sum_{j=2}^{\infty} A^a_{j,1s} r_j^{(2)} + C_{2s,1s} \quad , \qquad (2)$$

$$C^{CR}_{1s,2s} = \sum_{i=2}^{\infty} S_{i,2s} n_e r_i^{(1)} + \sum_{j=2}^{\infty} S_{j,2s} n_e r_j^{(1)} + C_{1s,2s} \quad , \qquad (3)$$

where S and C is ionization and excitation rate coefficients, respectively, and $A^a$ is autoionization rate.

The effective excitation rate coefficient 1s-2s of carbon ions (Z=6) is shown in Fig.1 at electron temperature $T_e = 3.5\times10^5$ (K). Excitation by the ladder-like mechanism exceed direct excitation from around $n_e = 10^{19}$ ($cm^{-3}$). Then as $n_e$ increase ladder-like mechanism 1s-1snl-2snl-2s dominant than dielectronic capture ladder-like excitation-ionization 1s-2snl-2s process. Density-dependence of the former process is proportional to $n_e$.

Fig.2. show the effective de-excitation rate coefficient. De-excitation by the ladder-like mechanism exceed direct de-excitation at around $n_e = 10^{18}$ ($cm^{-3}$). For increased density, the dependence of $C^{CR}_{2s,1s}$ is proportional to $n_e$ so that population density gradually reach LTE from high-n states. The ladder-like mechanism 2s-2snl-2pnl-1snl-1s dominate above $n_e \sim 10^{17}$ ($cm^{-3}$). The effect of 2snl-2pnl collisional process is factor of 4.5 at $n_e \sim 10^{18}$ ($cm^{-3}$) with result of model without 2snl-2pnl collisional process.

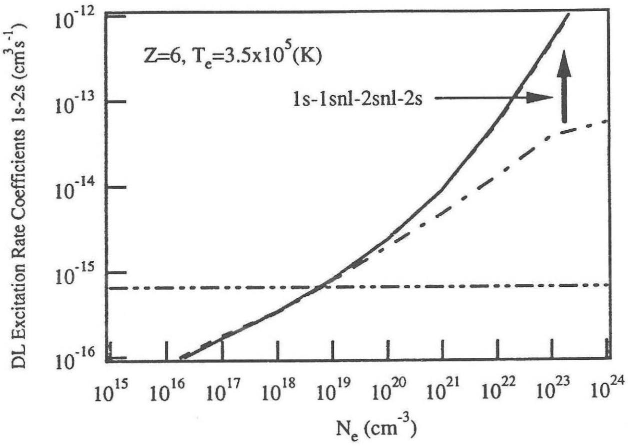


Fig.1. The effective excitation rate coefficients 1s-2s. Solid line: with 2snl-2pnl and 1snl'-2lnl'collisions, dashed line: without 2snl-2pnl collsion, dot-dashed line: without 1snl'-2lnl' collison and double dot-dashed line: direct excitation rate coefficient

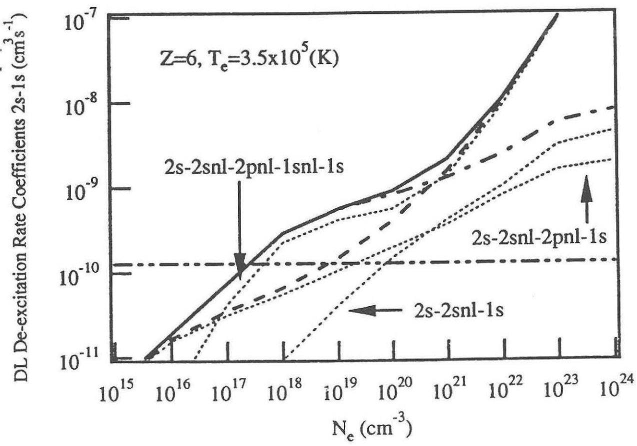


Fig.2. The effective de-excitation rate coefficients 2s-1s. Solid, dashed and dot dashed lines: same as Fig.1. Double dot-dashed line: direct de-excitation rate coefficient.

Refference
1) Fujimoto. T. and Kato. T., Phys. Rev. A35 (1987) 3024